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# CALCULATING THE BUSY PERIOD DISTRIBUTION OF THE M/M/1 QUEUE

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# Calculating the busy period distribution of the M/M/1 queue

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Programme I

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**Abstract**

This paper deals with the computation of the busy period distribution of the M/M/1 queue. We present a simple expression of this distribution, without any use of transforms or Bessel functions. This expression leads to an algorithm which performs the computation with an error tolerance specified by the user.

**Index Terms** – M/M/1 queue, busy period distribution, Catalan's numbers.

# Calcul de la distribution de la période d'activité de la file M/M/1

**Résumé**

Nous étudions dans ce rapport la distribution de la période d'activité du serveur d'une file M/M/1. Nous donnons une expression simple de cette distribution n'utilisant ni transformées, ni fonctions de Bessel. Cette expression conduit à un algorithme faisant le calcul avec une précision définie par l'utilisateur.

**Mots clés** – File M/M/1, distribution de la période d'activité, nombres de Catalan.

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# 1 Introduction

Several papers have been proposed for the numerical computation of the M/M/1 transient behaviour. We reference only one of the most recent, written by J. Abate and W. Whitt [1], in which numerous methods and references could be found for the analysis of this queue. It is interesting to note that almost all these papers are based on the use of Bessel functions.

In this paper, we focus on the busy period distribution of the M/M/1 queue. Using results on sojourn times in Markov processes [2], we derive a simple expression of this distribution avoiding Bessel functions. This expression is given in Section 2 and it holds for any value of the arrival and service rates. It consists of a series involving the Poisson distribution and Catalan's numbers. In Section 3, we show how to compute this series by truncating it such that its rest is as small as desired, and we give an algorithmic scheme to organize the computations. The last section is devoted to some conclusions.

# 2 The busy period distribution

Consider the classical M/M/1 queue with arrival rate $\lambda$ and service rate $\mu$. We denote by $A$ the infinitesimal generator of the continuous time Markov process associated to the state of the queue. The non zero entries of this matrix are

$$A(0,0) = -\lambda \text{ and for any } i \geq 1, \;\; A(i,i-1) = \mu, \;\; A(i,i) = -(\lambda+\mu), \;\; A(i,i+1) = \lambda.$$

Let $BP_i$, $i \geq 1$, be the duration of the $i$th busy period. If the initial state is state 0 or state 1, these random variables are i.i.d. The random variable $BP_i$ can be seen as the $i$th sojourn time of the process in the subset of states $\{1,2,\ldots\}$. Using the results obtained in [2] for finite Markov processes and observing that the transition rates of the M/M/1 queue are uniformly bounded (for every $i,j \geq 0$, $|A(i,j)| \leq \lambda+\mu$), it can be easily verified that the common distribution of these sojourn times denoted now by $BP$ is given by

$$\mathbb{P}(BP \leq t) = 1 - \alpha e^{A_1 t} 1^T \tag{1}$$

where $\alpha = (1,0,0,\ldots)$ and $A_1$ is the submatrix deduced from $A$ by deleting the row and the column corresponding to state 0. The row vector $1 = (1,1,1,\ldots)$ has all its entries equal to 1 and T denotes the transpose operator.

We consider now the embedded discrete time Markov chain at the instants of state change and we denote by $P$ its transition probability matrix. In the same way as for matrix $A$, we define $P_1$ as the submatrix deduced from $P$ by deleting the row and the column corresponding to state 0. For every $i \geq 1$, the non zero entries of $P_1$ are

$$P_1(i,i-1) = \frac{\mu}{\lambda+\mu}, \;\; P_1(i,i+1) = \frac{\lambda}{\lambda+\mu}.$$

In matrix notation, we have

$$P_1 = I + \frac{1}{\lambda + \mu} A_1$$

or equivalently,

$$A_1 = -(\lambda + \mu)(I - P_1),$$

where $I$ denotes the identity matrix. Relation (1) can be now written

$$\begin{aligned}
\mathbb{P}(BP \leq t) &= 1 - \alpha e^{-(\lambda+\mu)(I-P_1)t} 1^T \\
&= 1 - e^{-(\lambda+\mu)t} \sum_{k=0}^{+\infty} \frac{(\lambda+\mu)^k t^k}{k!} \alpha P_1^k 1^T \\
&= \sum_{k=0}^{+\infty} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \left(1 - \alpha P_1^k 1^T\right).
\end{aligned}$$

Let us denote by $N$ the number of states visited during a busy period. For every $i \geq 1$ and $k \geq 0$, we denote by $\mathbb{P}_i(N = k)$ the probability that the number of states visited during a busy period is equal to $k$ given that the initial state is $i$. Defining

$$p \equiv \frac{\lambda}{\lambda + \mu} \text{ and } q \equiv \frac{\mu}{\lambda + \mu},$$

we obtain the following renewal equations:

$$\begin{aligned}
\mathbb{P}_i(N = 0) &= 0 && \text{for every } i \geq 1, \\
\mathbb{P}_1(N = 1) &= q, && \\
\mathbb{P}_i(N = 1) &= 0 && \text{for every } i \geq 2, \\
\mathbb{P}_1(N = k) &= p\mathbb{P}_2(N = k-1) && \text{for every } k \geq 2, \\
\mathbb{P}_i(N = k) &= p\mathbb{P}_{i+1}(N = k-1) + q\mathbb{P}_{i-1}(N = k-1) && \text{for every } i \geq 2 \text{ and } k \geq 2.
\end{aligned}$$

Denoting by $V(k)$, $k \geq 0$, the column vector with $i$th entry, $i \geq 1$, equal to $\mathbb{P}_i(N = k)$, the previous relations can be written in matrix notation as

$$V(0) = 0, \quad V(1) = q\alpha^T, \quad V(k) = P_1 V(k-1) \text{ for every } k \geq 2.$$

The column vector $V(1)$ can also be written as $V(1) = (I - P_1)1^T$. We then deduce that, for every $k \geq 1$,

$$V(k) = P_1^{k-1}(I - P_1)1^T$$

and

$$\mathbb{P}_1(N = k) = \alpha V(k) = \alpha P_1^{k-1}(I - P_1)1^T.$$

It follows that

$$\mathbb{P}_1(N \leq k) = 1 - \alpha P_1^k 1^T \text{ for every } k \geq 0.$$

Moreover, since the initial state has been choosen to be 0, we set

$$\mathbb{P}(N \leq k) \equiv \mathbb{P}_0(N \leq k) = \mathbb{P}_1(N \leq k).$$

These considerations lead to the following formula for the busy period distribution:

$$\begin{aligned}
\mathbb{P}(BP \le t) &= \sum_{k=0}^{+\infty} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \mathbb{P}(N \le k) \\
&= \sum_{k=1}^{+\infty} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \mathbb{P}(N \le k).
\end{aligned}$$

It is well known [3] that the probability of serving $n$ customers in a busy period starting in state 1 is

$$\binom{2n-2}{n-1} \frac{p^{n-1} q^n}{n}.$$

The number of customers served in a busy period is $r+1$ iff the number of states visited in a busy period is $2r+1$. So, we obtain that for every $r \ge 0$,

$$\mathbb{P}(N = 2r+1) = \binom{2r}{r} \frac{p^r q^{r+1}}{r+1}$$

and obviously, we have $\mathbb{P}(N = 2r) = 0$ for every $r \ge 0$. For $r \ge 0$, the integers

$$\binom{2r}{r} \frac{1}{r+1}$$

are known as the Catalan's numbers. The distribution of the busy period becomes

$$\mathbb{P}(BP \le t) = \sum_{k=1}^{+\infty} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \sum_{r=1}^{k} \mathbb{P}(N = r),$$

that is,

$$\mathbb{P}(BP \le t) = \sum_{k=1}^{+\infty} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \sum_{r=0}^{\lfloor \frac{k-1}{2} \rfloor} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1}. \tag{2}$$

Observe that

$$\lim_{t \to +\infty} \mathbb{P}(BP < t) = \sum_{r=0}^{+\infty} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1}.$$

It can be shown (see for instance [4]) that for $0 < x \le 1/4$,

$$\sum_{r=0}^{+\infty} \binom{2r}{r} \frac{x^r}{r+1} = \frac{1 - \sqrt{1-4x}}{2x}.$$

Here, $pq \le 1/4$ since $p + q = 1$, so

$$\sum_{r=0}^{+\infty} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} = \frac{1 - \sqrt{1-4pq}}{2p} = \begin{cases} 1 & \text{if } p \le \frac{1}{2} \\ \frac{1-p}{p} & \text{if } p > \frac{1}{2} \end{cases}$$

This remark leads to the well-known result:

$$\lim_{t\longrightarrow+\infty} \mathbb{P}(BP < t) = \begin{cases} 1 & \text{if} \quad \lambda \le \mu, \\ \frac{\mu}{\lambda} & \text{if} \quad \lambda > \mu. \end{cases}$$

We will denote by $h(\lambda,\mu)$ this limit, that is,

$$h(\lambda,\mu) \equiv \min\left\{1, \frac{\mu}{\lambda}\right\}.$$

# 3 Computing the busy period distribution

In this section, we consider formula (2) in two different ways. In Subsection 3.1, we perform a truncation over index $k$ such that the rest of the series becomes less than or equal to a given error tolerance $\varepsilon$. In Subsection 3.2, we permute the two sums in formula (2) and we perform a truncation over index $r$ with the same error tolerance $\varepsilon$. The third subsection gives an outline on the computation of the distribution of the busy period. The reasons of these manipulations will appear along the discussion.

## 3.1 Truncating over index $k$

To compute the distribution of the busy period, we have first to evaluate the truncation step $K$ in order to have the rest of the series (2) less than or equal to a given error tolerance $\varepsilon$. Denoting by $e(K)$ the rest of this series, we have

$$\begin{aligned} e(K) &= \sum_{k=K+1}^{+\infty} e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!} \sum_{r=0}^{\lfloor\frac{k-1}{2}\rfloor} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \\ &\le h(\lambda,\mu) \sum_{k=K+1}^{+\infty} e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!} \\ &= h(\lambda,\mu)\left(1 - \sum_{k=0}^{K} e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!}\right). \end{aligned}$$

The integer $K$ is choosen as the smallest one verifying

$$h(\lambda,\mu)\left(1 - \sum_{k=0}^{K} e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!}\right) \le \varepsilon. \tag{3}$$

We then have the following result:

$$0 \le \mathbb{P}(BP \le t) - \sum_{k=1}^{K} e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!} \sum_{r=0}^{\lfloor\frac{k-1}{2}\rfloor} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \le \varepsilon.$$

So, $\mathbb{P}(BP \le t)$ can be computed using the following expression, with a precision equal to $\varepsilon$:

$$\sum_{k=1}^{K} e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!} \sum_{r=0}^{\lfloor\frac{k-1}{2}\rfloor} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1}. \tag{4}$$

The number of terms that must be computed using this formula is equal to $(K+1)^2/4$ if $K$ is odd, and to $K(K+2)/4$ if $K$ is even.

### 3.2 Truncating over index $r$

Let us first permute the two sums in formula (2). We obtain

$$\mathbb{P}(BP \leq t) = h(\lambda,\mu) - \sum_{r=0}^{+\infty} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \sum_{k=0}^{2r} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!}.$$

Using the same argument as in the previous subsection, we get

$$\mathbb{P}(BP \leq t) = h(\lambda,\mu) - \sum_{r=0}^{R} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \sum_{k=0}^{2r} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} - e'(R)$$

where

$$\begin{aligned} e'(R) &= \sum_{r=R+1}^{+\infty} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \sum_{k=0}^{2r} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \\ &\leq \sum_{r=R+1}^{+\infty} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \\ &= h(\lambda,\mu) - \sum_{r=0}^{R} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1}. \end{aligned}$$

So, integer $R$ is choosen as the smallest one verifying

$$h(\lambda,\mu) - \sum_{r=0}^{R} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \leq \varepsilon. \tag{5}$$

We then have

$$-\varepsilon \leq \mathbb{P}(BP \leq t) - \left[ h(\lambda,\mu) - \sum_{r=0}^{R} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \sum_{k=0}^{2r} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!} \right] \leq 0.$$

This result allows to compute $\mathbb{P}(BP \leq t)$, with a precision equal to $\varepsilon$, by the following expression:

$$h(\lambda,\mu) - \sum_{r=0}^{R} \binom{2r}{r} \frac{p^r q^{r+1}}{r+1} \sum_{k=0}^{2r} e^{-(\lambda+\mu)t} \frac{(\lambda+\mu)^k t^k}{k!}. \tag{6}$$

The number of terms that must be computed using this formula is equal to $(R+1)^2$.

### 3.3 Algorithm

The two previous subsections lead naturally to a simple algorithm which uses expressions (4) or (6) depending on the values of the truncation steps $K$ and $R$. The choice between these two expressions can be done by considering the number of terms appearing in their sums. These numbers of terms have been evaluated in each of the two previous subsections. It follows that if $K \leq 2R$ we shall use expression (4) and otherwise we shall use expression (6). This decision can be taken in the following way. Relations (3) and (5) are tested in the same loop and the first one satisfied will determine the corresponding truncation step and so the best expression that must be used. In all cases, the result is obtained with a precision $\varepsilon$ given by the user.

One can note that the integer $K$ is a function of $\lambda$, $\mu$, $\varepsilon$ and $t$, where $R$ is only a function of $\lambda$, $\mu$ and $\varepsilon$. Moreover, it is easy to verify that if $t \leq t'$ then $K(\lambda,\mu,\varepsilon,t) \leq K(\lambda,\mu,\varepsilon,t')$. It follows that if relation (5) is the first satisfied for the value $t$, it will be also the first satisfied for all values greater than $t$. A general algorithm to compute the distribution of the busy period in $M$ points $t_1 < \cdots < t_M$ can be written in the following way. For every integers k and r, we will use the notation:

$$\text{poi(k,t)} \equiv e^{-(\lambda+\mu)t}\frac{(\lambda+\mu)^k t^k}{k!} \quad \text{and} \quad \text{cat(r)} \equiv \begin{pmatrix} 2r \\ r \end{pmatrix} \frac{p^r q^{r+1}}{r+1}.$$

**input** : $\lambda$, $\mu$, $\varepsilon$, $t_1 < \cdots < t_M$
**output** : $\mathbb{P}(BP \leq t_1), \ldots, \mathbb{P}(BP \leq t_M)$
**initialisation** : chooseR := **false**; R := 0; K := 0; i := 0; sumcat := cat(0)
  **while** [ **not** chooseR **and** $i \leq M$ ] **do**
    i := i + 1
    sumpoi := poi(0,$t_i$)
    **for** l := 1 **to** K **do** sumpoi := sumpoi + poi(l,$t_i$) **endfor**
    **while** [ $h(\lambda,\mu)(1 - \text{sumpoi}) > \varepsilon$ **and** $h(\lambda,\mu) - \text{sumcat} > \varepsilon$ ] **do**
      K := K + 2
      sumpoi := sumpoi + poi(K-1,$t_i$) + poi(K,$t_i$)
      R := R + 1
      sumcat := sumcat + cat(R)
    **endwhile**
    **if** $h(\lambda,\mu)(1 - \text{sumpoi}) \leq \varepsilon$ **then** $\mathbb{P}(BP \leq t_i)$ := Expression (4)
    **else** $\mathbb{P}(BP \leq t_i)$ := Expression (6); chooseR := **true**
    **endif**
  **endwhile**
  **for** j := i+1 **to** M **do** $\mathbb{P}(BP \leq t_j)$ := Expression (6) **endfor**

The first execution of the outer **while** loop is done for the value K=0, so that the **for** loop on index l is skipped. Assume that the inner **while** loop is left because $h(\lambda,\mu)(1 - \text{sumpoi}) \leq \varepsilon$. The busy period distribution is then computed using Expression (4) and the second value $t_2$ is considered. Note that the current values of the variables K and R are respectively $K(\lambda,\mu,\varepsilon,t_1)$ and $K(\lambda,\mu,\varepsilon,t_1)/2$ (this is due to the fact that the variable sumpoi cumulates two values at each step and the variable sumcat only one). At this point, the value of the variable sumcat is cat(0) + $\cdots$ + cat(R). Since $t_2 > t_1$, we know that $K(\lambda, \mu, \varepsilon, t_2) \geq K(\lambda, \mu, \varepsilon, t_1)$; moreover, recall that the truncation step $R$ is independent of the values of $t_i$. That is why the **for** loop on index l is executed to compute the sum sumpoi of poi(l,$t_2$) for l $\leq$ K $= K(\lambda, \mu, \varepsilon, t_1)$. From that instant, the control passes to the inner **while** loop as in the first iteration step. It can be observed that the effective implementation of this algorithm needs some tradeoff between computing time and storage. Many intermediate calculations appearing in expressions (4) and (6) are performed when taking the decision on which of the two relations will be used. On the computations themselves, in addition of trivial points as the recurrent definition of poi(k,t) as a function of poi(k-1,t) or cat(r) as a function of cat(r-1), the reader can consult for instance [5] for some concerns on the underflow problem due to the exponential.

Remark that the choice between expressions (4) and (6) can lead to a considerable gain in computing time. Indeed, let for instance $\mu = 1.0$, $t = 100$ and $\varepsilon = 10^{-6}$. For $\lambda = 1.05$, we obtain $K = 276$ and $R = 9908$. For $\lambda = 0.99$, the corresponding values are $K = 270$ and $R = 166139$. On the other hand, for $\lambda = 10$, we obtain $K = 1244$ and $R = 7$.

## 4 Conclusions

In this paper, we have developped a simple algorithm to compute the busy period distribution of the M/M/1 queue. To obtain it, we have used results on sojourn times in Markov processes and Catalan's numbers. Further work could be the extension of the proposed method to the computation of other time-dependent measures for this queue and for similar models.

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